SHUTTLE FLOW FIELD ANALYSIS USING THE DIRECT SIMULATION MONTE CARLO TECHNIQUE

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1. INTRODUCTION

The theoretical evaluation of the performance of a molecular shield[1] requires a detail description of the flow field properties in the immediate vicinity of the Shuttle. Knowledge of the flow field properties is essential in determining the molecular shield-to-Shuttle separation distance; the orientation of the shield deployment boom with respect to the Shuttle axis; and the influence on shield performance due to molecular scattering, due to molecular reflection from the Shuttle surface, due to outgassing from the Shuttle surface, and due to Shuttle related gas sources such as leaks, vents, dumps and attitude control rockets. Optimization of the shield performance requires the investigation of the flow field properties for a range of Shuttle orbital attitudes and orbit heights.

From an investigation of analytical and numerical techniques which are capable of analyzing three-dimensional, external, rarified gas flow the Direct Simulation Monte Carlo Technique[2] was selected as the most useful in solving the Shuttle flow field problem.

Bird[2] has shown that the Direct Simulation Monte Carlo technique yields the numerical equivalent of a solution for the time dependent Boltzmann transport equation with boundary conditions. This is a

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[1] Melfi, L. T., Characteristics and potential applications of orbiting ultrahigh vacuum facilities, Acta Astronautica 4:801-811 (1977).

[2] Bird, G. A., Molecular Gas Dynamics, Oxford University Press (London) 1976.

self-consistent technique which honors all the conservation laws applicable to real gas flow. The technique has the capability of analyzing three-dimensional flow with internal and external boundary conditions; transient flow phenomena by ensenble averaging; and steady state phenomena by time averaging.

Molecular modeling equations are used to obtain the modeled molecule cross section and the molecular collision frequency density. The modeled cross section σ is obtained from

$$\sigma = \frac{1}{\sqrt{2}\lambda n} , \qquad (1)$$

where λ is the mean free path and n is the modeled density. The molecular collision frequency density is obtained from (for a single species gas)

$$N_c = \frac{1}{2} n^2 \sigma \bar{v}_r , \qquad (2)$$

where N_c is the modeled molecular collision frequency per unit volume and $\bar{v}_r$ is the mean relative speed. The assumption is made that the molecular motion process and the molecular collision process may be treated as uncoupled provided the molecular motion time increment Δt_m is small compared to the mean time between molecular collisions. The validity of this assumption has been demonstrated(2) theoretically and experimentally. Molecular trajectories are calculated using the classical laws of motion and molecular collisions are calculated using classical collision dynamics.

2. COMPUTATIONAL PROCEDURE

A scale drawing of the Shuttle is shown in Figure 1. A close approximation of the Shuttle geometrical configuration has been written into the Shuttle flow field analysis program code.[3] The Shuttle surface is divided into 38 surface elements as shown in Figure 2 which are also written into the program code. Either of two options may be selected at execution time, payload bay doors open or closed. Figure 3 gives the flow field geometry and the location of the Shuttle within the flow field. The flow field is divided into seven blocks, each of which is subdivided into many computational cells. The location of the flow field boundaries, the location of the block boundaries, and number of computational cells in each block are selected at execution time. The flow field volume is typically of the order of $10^6 m^3$. The number of cells in the flow field typically ranges between 500 and 700. The Shuttle midplane is a plane of symmetry. The angle of attack α (angle between the free stream velocity and + x) is selected at execution time.

The molecular flux density incident on the flow field boundaries from the outside is calculated (internally) from the drifting

[3] Bird, G. A., Flow field simulation for the space Shuttle orbital vehicle, Proc. 10th Int. Symp. Rarefied Gas Dynamics (1976).

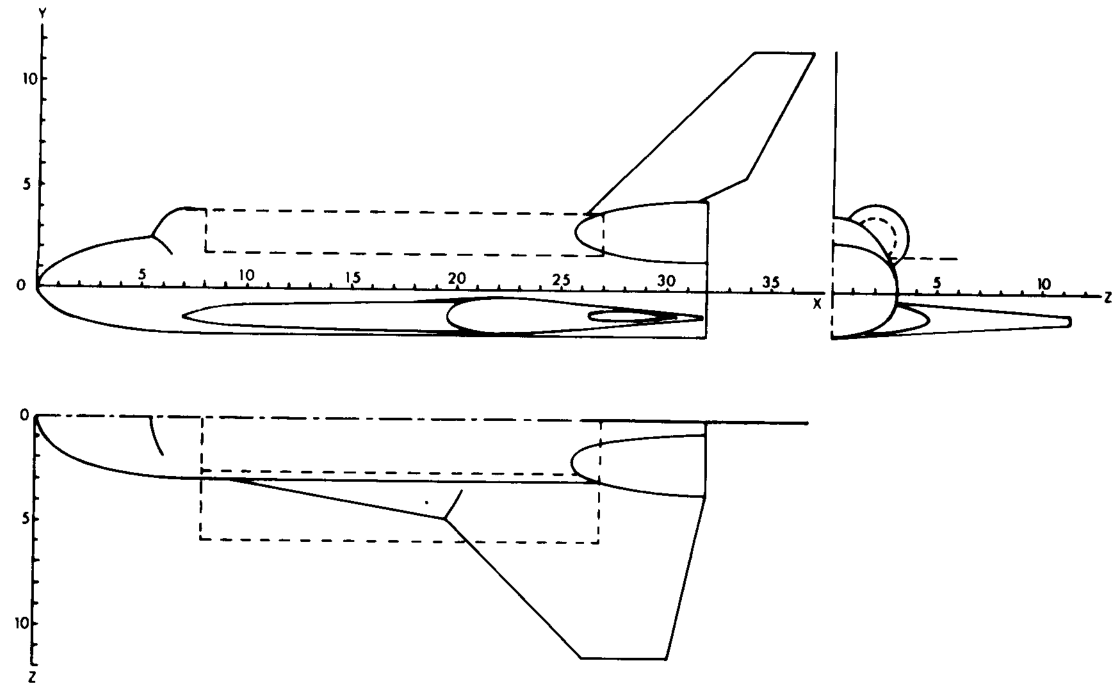

Fig. 1. Shuttle geometry (dimensions in meters). The midplane (z=0) is a plane of symmetry. A close approximation of the actual Shuttle geometry is written into the flow field analysis program code.

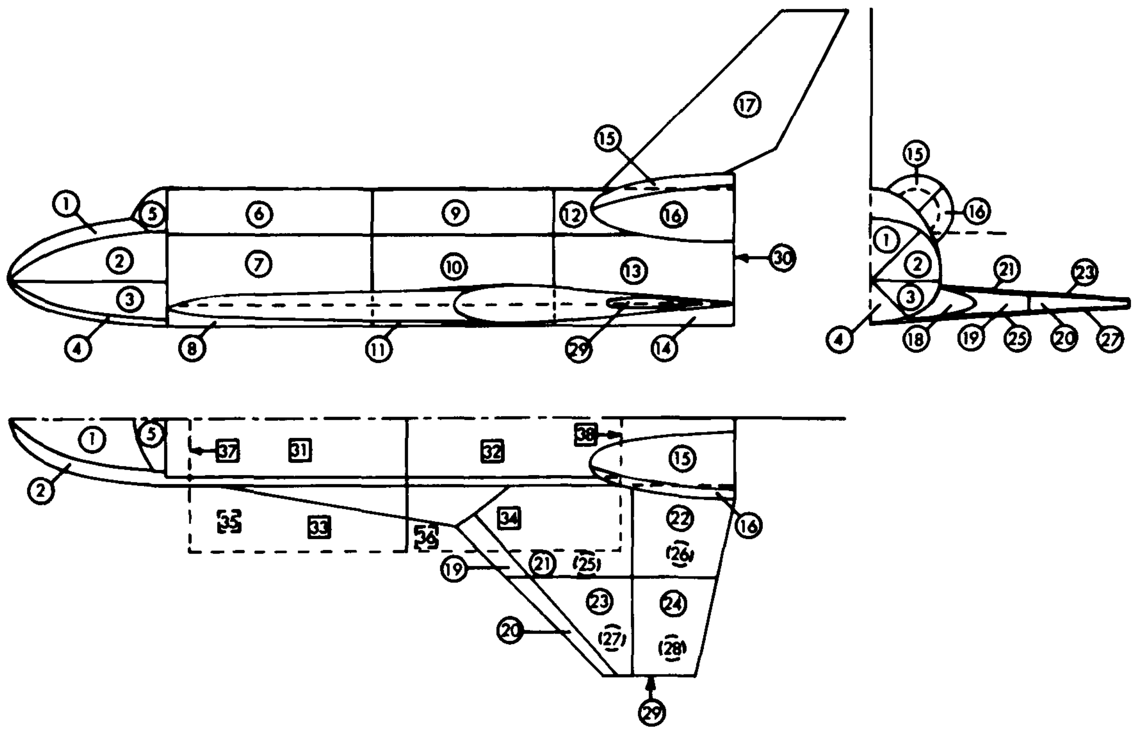

Fig. 2. The geometrical configuration of the Shuttle surface elements written into the flow field analysis program code. The numbers in solid symbols refer to surface elements in direct view, the numbers in dashed symbols refer to elements on the opposite side of the surface. The square symbols refer to the doors-open configuration only.

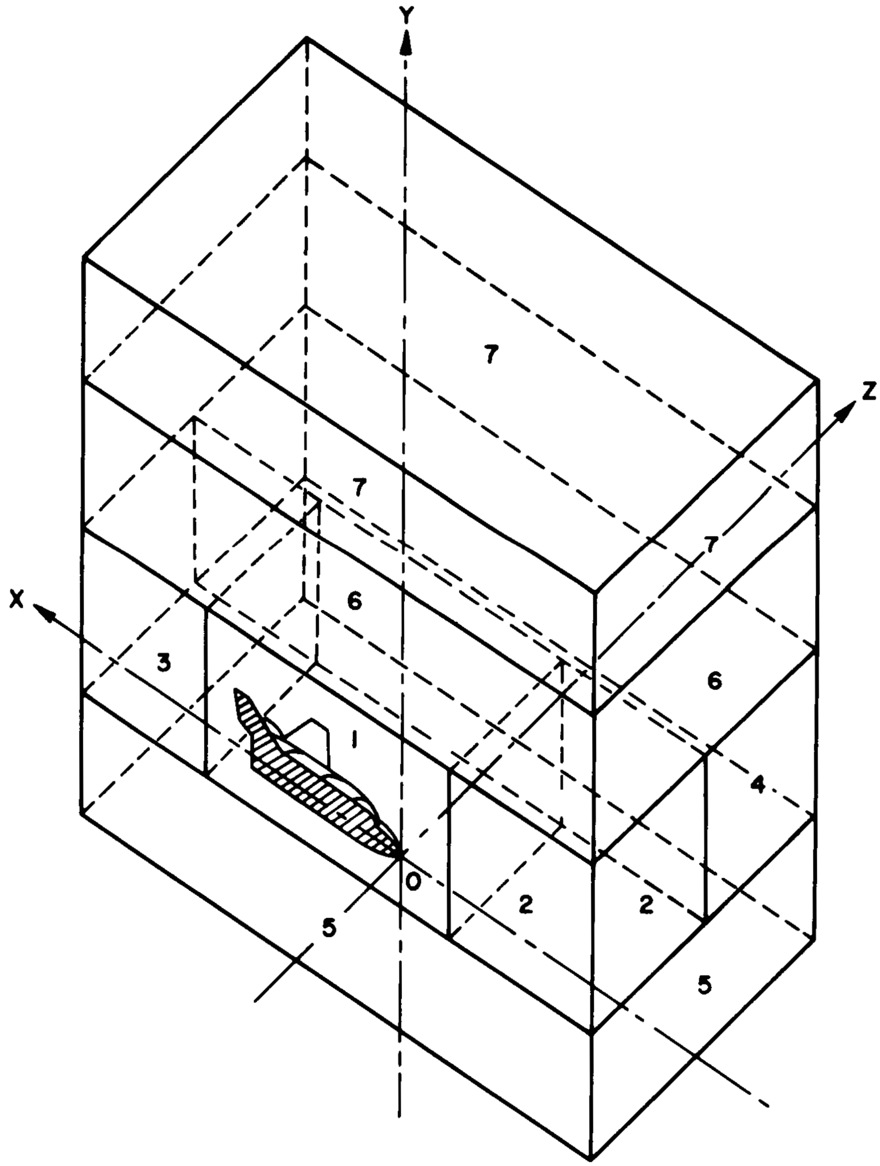

Fig. 3. The flow field geometrical configuration and the location of the Shuttle within the flow field. The midplane (z=0) is a plane of symmetry.

Maxwellian gas properties of the free stream. The stream drift velocity, the mean free path, and the mean thermal speed are specified at execution time (the free stream density is a modeled parameter). The molecular flux entering the flow field from the Shuttle surface (outgassing) is randomly distributed over each surface element and is assumed to be in thermal equilibrium with the surface at emission. The molecular emission angular distribution is assumed to obey the cosine law. Molecules which are incident on the Shuttle surface are assumed to equilibrate to the surface temperature before reflection. These reflected molecules are also assumed to obey the cosine law. The outgassing flux density is specified at execution time. Molecular fluxes may enter the flow field from a prescribed number of discrete sources located on or near the Shuttle. The location, emission direction, molecular velocity distribution, angular distribtuion, and emission flux of these discrete sources are specified at execution time.

The Shuttle flow field analysis program keeps continuous and separate account of five types of molecules: type 1, free stream molecules; type 2, free stream molecules which have been reflected from the Shuttle surface; type 3, free stream molecules which have experienced a molecular collision with other molecular types (excluding type 1); type 4, Shuttle outgassing molecules; and type 5, Shuttle discrete gas source molecules (such as leaks, vents, dumps, and attitude control rockets). There are two options for the molecular cross section, hard sphere or inverse ninth power, one of which is selected at execution time.

A schematic flow diagram of the Monte Carlo program is shown in Figure 4. The program maintains the position and velocity components current for each modeled molecule from the time it enters the flow field until it exits. The main program loop starts at 103, the flow field properties sampling loop starts at 112, and the incremental flow analysis loop starts at 111. At 116 molecular trajectory increments corresponding to Δt_m are calculated, including Shuttle surface collisions, block and field boundary interactions, etc. At 117 molecules enter the flow field from all sources and then molecular collisions are calculated.

The value of Δt_m is typically between 1 and 10 ms, NIS is typically between 1 and 5 and NSP is typically between 10 and 100. The number of passes through loop 103 depends largely on the problem, the resolution desired, the statistical fluctuation considered acceptable, and the kind of averaging required by the problem (ensemble or time). Depending on these same parameters, execution time may range between 0.5 and 20 hours in a Cyber 175.

3. DISCUSSION OF RESULTS

A number of Shuttle flow field configurations are presently under analysis and results from one of these is presented in the following

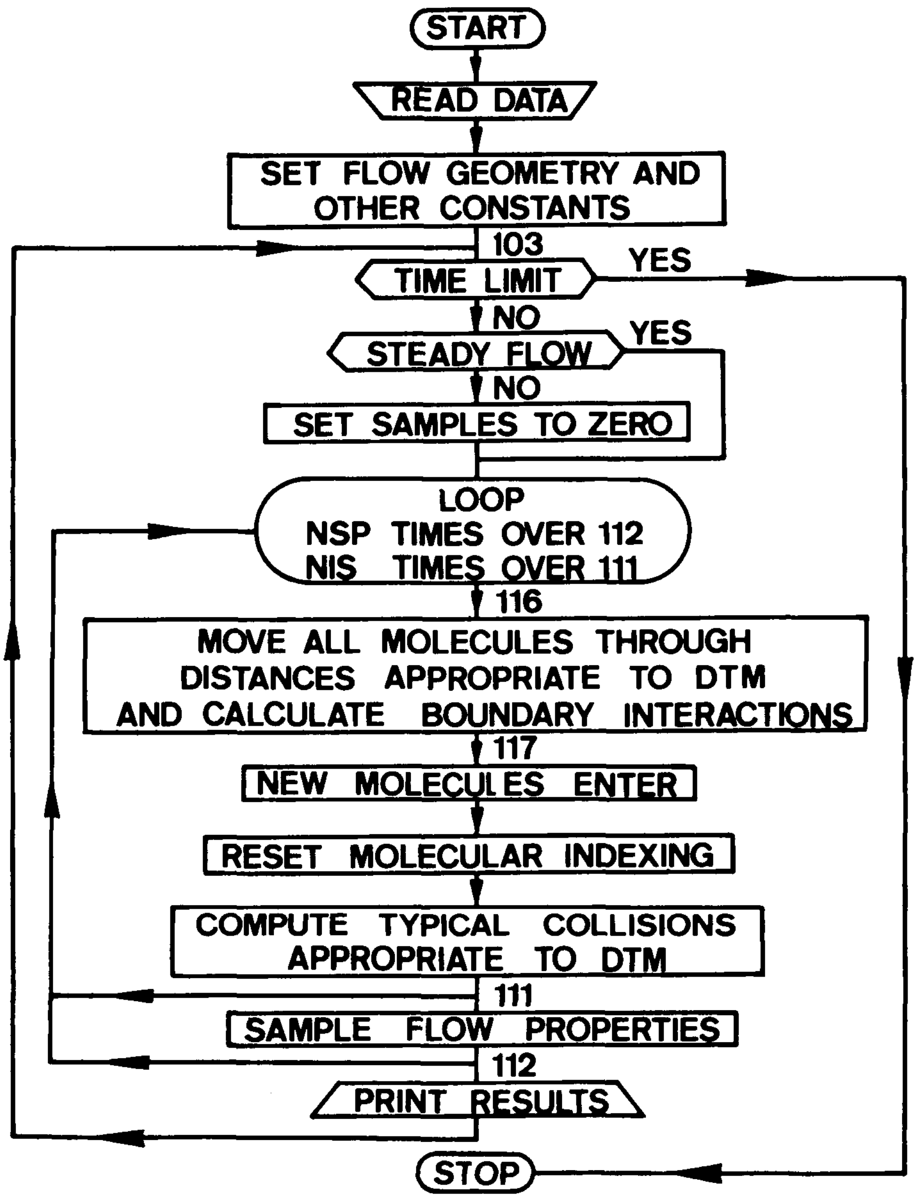

Fig. 4. Schematic flow diagram of the Monte Carlo, Shuttle flow field analysis program.

figures. To minimize the complexity of the illustrations only data in the Shuttle midplane are presented. Thus, the two-dimensional contour curves presented are the result of making a midplane cut through three-dimensional contour surfaces. Figures 5 through 12 give the results of a flow field analysis in which the free stream density $n = 8.33 \times 10^9 cm^{-3}$, the velocity $u = 7790$ m/sec, the temperature $T = 855K$, and the mean free path $\lambda = 386$ m. The Shuttle surface outgassing rate $\nu_{og} = 10^{15} cm^{-2} sec^{-1}$, the surface temperature $T_s = 300K$, and the angle of attack $\alpha = 0$. A tilda is used to indicate a normalized parameter. Densities are normalized by the free stream density and flux densities are normalized by the flux density in the stationary free stream $\nu = n\, v_m/(2\sqrt{\pi}) = 2.2 \times 10^{14} cm^{-2} sec^{-1}$.

Figure 5 gives the normalized density distribution of type 1 molecules in the Shuttle midplane. These are free stream molecules which have not collided with the Shuttle surface and which have not been collisionally affected. The shapes of these contours are principally determined by collisions between free stream molecules and molecules which were either reflected from the surface or emitted from the surface due to outgassing. As free stream molecules pass through regions where the reflected or outgassed molecule density is relatively high, the integral collision probability increases. This implies that an increasing fraction of the type 1 molecules are converted to type 3 as a result of collisions with reflected and outgassed molecules, and the type 1 density decreases. Thus, the type 1

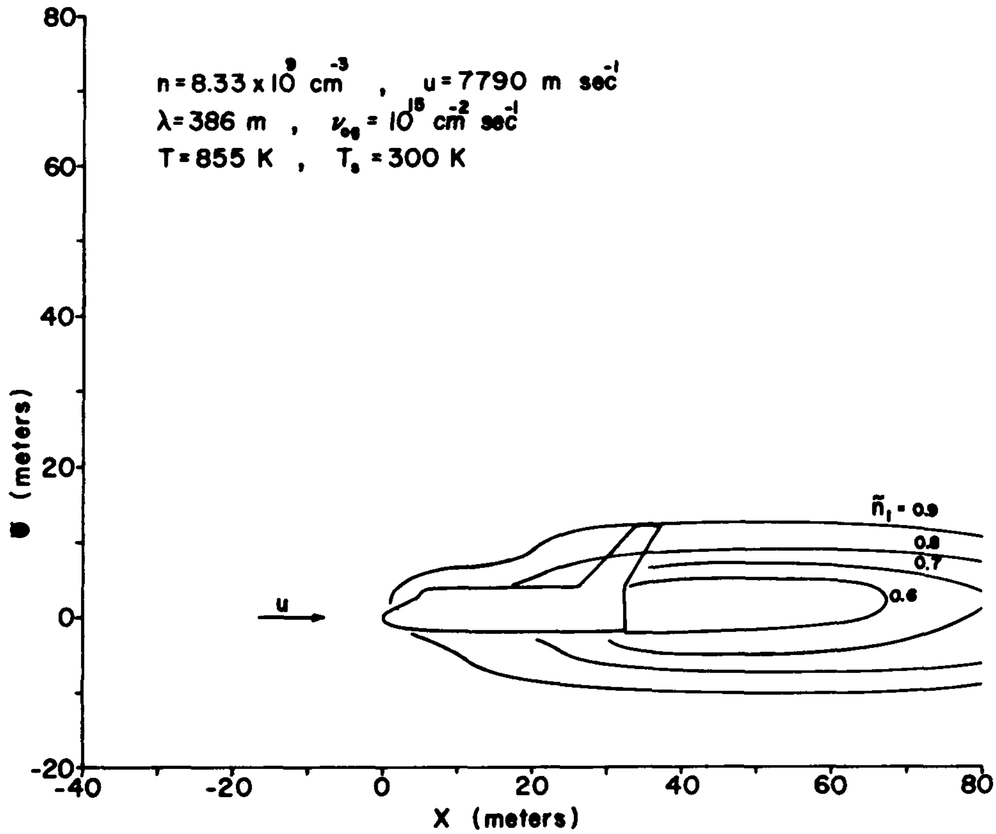

Fig. 5. The density distribution of freestream molecules (type 1) in the Shuttle midplane, normalized by the undisturbed freestream density $n=8.33 \times 10^9$ cm^{-3}. The freestream velocity u=7790 m sec^{-1}, the temperature T=855 K, and the mean free path λ=386 m. The Shuttle surface temperature T_s=300 K, and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

contours ($\tilde{n}_1 < 1$) expand in the transverse direction as they are followed in the longitudinal direction (aft). Well aft of the Shuttle, the entire process is reversed and the contours collapse.

Figure 6 gives the normalized density distribution of type 2 molecules (free stream molecules which have been reflected from the Shuttle surface) in the Shuttle midplane. The contour $\tilde{n}_2 = 1$ near the nose of the Shuttle is obviously associated with the well known ram effect. This observation also applies to the bulge in this contour above the fuselage near the aft end since the engine pods present a substantial effective frontal area to the flow. In the center fuselage region, two effects combine to produce a decrease in the density of reflected molecules $\tilde{n}_2$: (1) Most of the surface element normals are nearly orthogonal to the free stream velocity and the incident free stream flux density is much lower, since $n\, v_m/(2\sqrt{\pi}) = 2.2 \times 10^{14} cm^{-2} sec^{-1}$ which is much smaller than the ram flux density which is approximately $n\, u = 6.5 \times 10^{15} cm^{-2} sec^{-1}$. (2) The free stream density is lower in this region due to upstream (previous) collisions. It may be observed that $\tilde{n}_2$ decreases more rapidly in the transverse direction than $1/y^2$ but that in the forward longitudinal direction $\tilde{n}_2$ decreases less rapidly than $1/x^2$. This is due to the difference in reflected flux density discussed above and to momentum transfer from the free stream to reflected molecules during collisions.

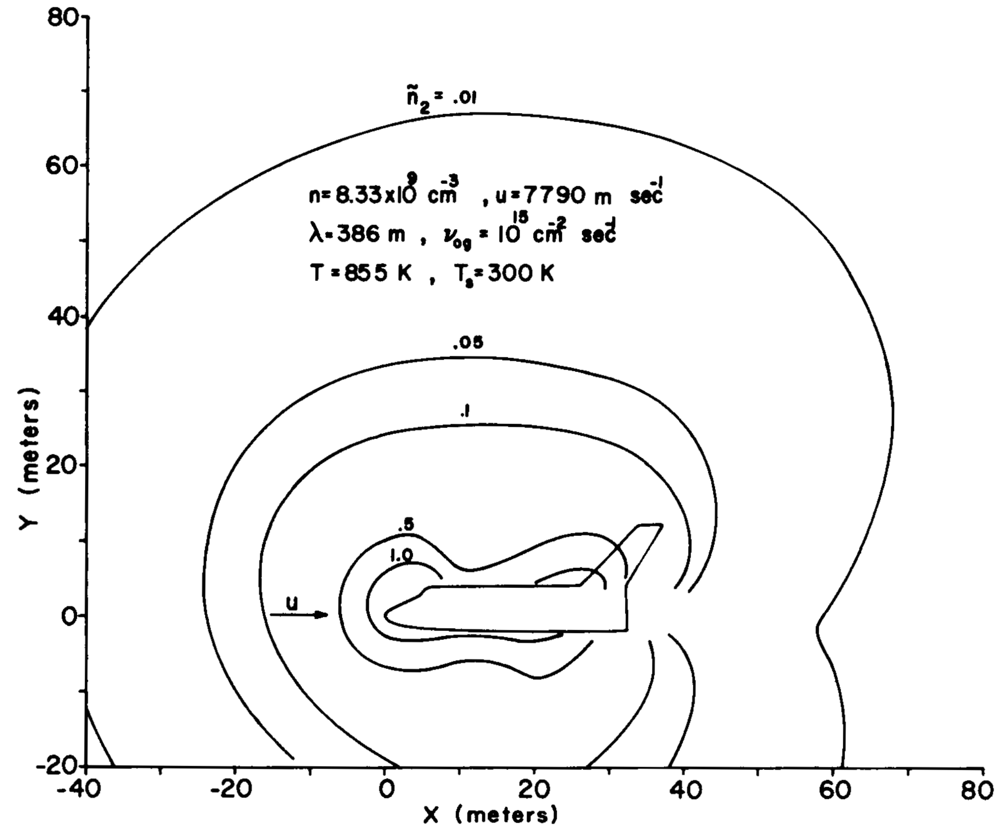

Fig. 6. The density distribution of reflected freestream molecules (type 2) in the Shuttle midplane, normalized by the undisturbed freestream density n=8.33 x 10^9 cm^{-3}. The freestream velocity u=7790 m sec^{-1}, the temperature T=855 K and the mean free path λ=386 m. The Shuttle surface temperature T_S=300 K, and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

Figure 7 gives the normalized density distribution of type 3 molecules (free stream molecules which have been collisionally affected by reflected or outgassed molecules) in the Shuttle midplane. $\tilde{n}_3$ increases moving aft due to the increasing integral probability of collisional conversion of type 1 molecules to type 3 and due to the increase in the combined type 2 and type 4 density. The relatively low value of $\tilde{n}_3$ is consistent with the relatively long mean free path in the free stream since the Shuttle outgassing rate is not sufficiently high that it dominates the mean free path in the flow field. The shape of the contours also imply that in the mean the type 3 molecules after conversion collision, retain a substantial fraction of their original momentum (while type 1) which is consistent with a first collision interaction.

Figure 8 gives the normalized density distribution of type 4 molecules (Shuttle outgassed molecules) in the Shuttle midplane. In the vicinity of the Shuttle, $\tilde{n}_4$ increases moving aft since a larger fraction of the surface area is aft (engine pods, vertical fin, wings). In this flow field analysis the outgassing flux density is uniform over the surface of the Shuttle. Over much of the volume near the Shuttle, the density of outgassing molecules $\tilde{n}_4$ exceeds the density of reflected molecules $\tilde{n}_2$. This confirms the conclusion that much of the type 1 scattering is due to collisions with type 4. It also explains the similarity in shape of the $\tilde{n}_3$ and $\tilde{n}_4$ contours near the Shuttle.

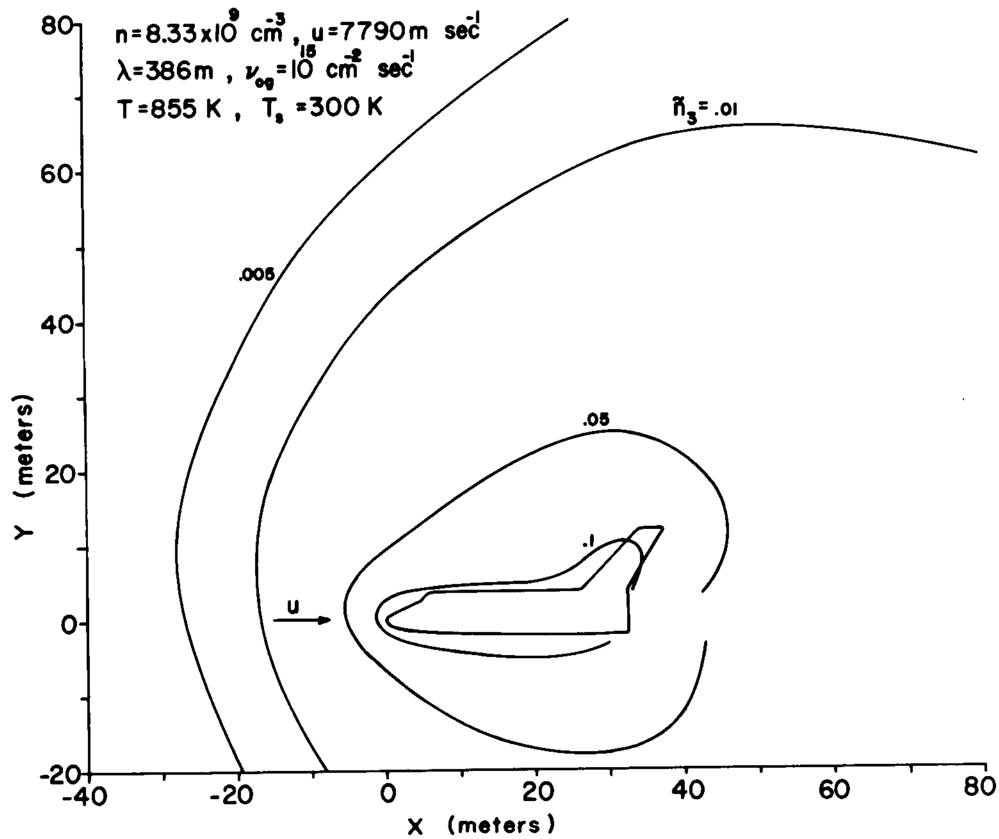

Fig. 7. The density distribution of collisionally affected freestream molecules (type 3) in the Shuttle midplane, normalized by the undisturbed freestream density n=8.33 x 10^9 cm^{-3}. The freestream velocity u=7790 m sec^{-1}, the temperature T=855 K, and the mean free path λ=386 m. The Shuttle surface temperature T_S=300 K and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

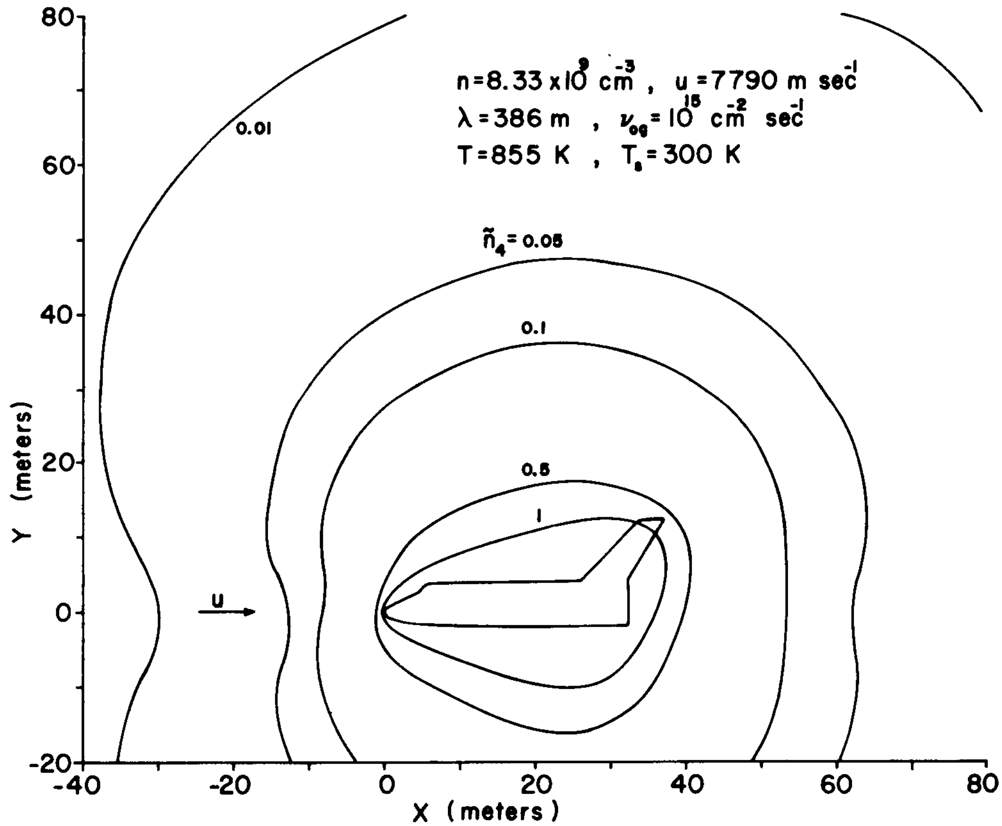

Fig. 8. The density distribution of Shuttle outgassed molecules (type 4) in the Shuttle midplane, normalized by the undisturbed freestream density $n=8.33 \times 10^9$ cm^{-3}. The freestream velocity $u=7790$ m sec^{-1}, the temperature T=855 K, and the mean free path $\lambda=386$ m. The Shuttle surface temperature $T_s=300$ K and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

Figure 9 gives the total density distribution (summed over all molecule types) in the Shuttle midplane. Close to the Shuttle, the principal contribution to the total density is from outgassed molecules and reflected molecules. At distances larger than one Shuttle length away the principal contribution to the total density is from free stream molecules. It may be observed that the total density differs from the free stream density by less than 10 percent for distances greater than two Shuttle lengths away from the Shuttle.

Figure 10 gives the normalized upstream flux density distribution in the Shuttle midplane (summed over all molecule types). Near the Shuttle the upstream flux is principally due to emission of outgassing molecules with an upstream velocity component and secondarily to reflected molecules which were emitted with an upstream component. However, at several Shuttle lengths away and especially aft of the Shuttle substantially all the upstream flux is due to molecules which have experienced multiple collisions while in the flow field or to molecules which entered the flow field such that the angle between their trajectory and the free stream velocity is relatively large. The data in Figure 10 imply that experiments in a molecular shield deployed on a 75 m boom and oriented 45^{o} aft of vertical would experience 0.1 percent surface coverage in approximately 10 hours. Immediately above the payload bay $\tilde{\nu}_{-x} = 3$ which implies that considerable attention must be given to protecting any sensitive experiment during deployment.

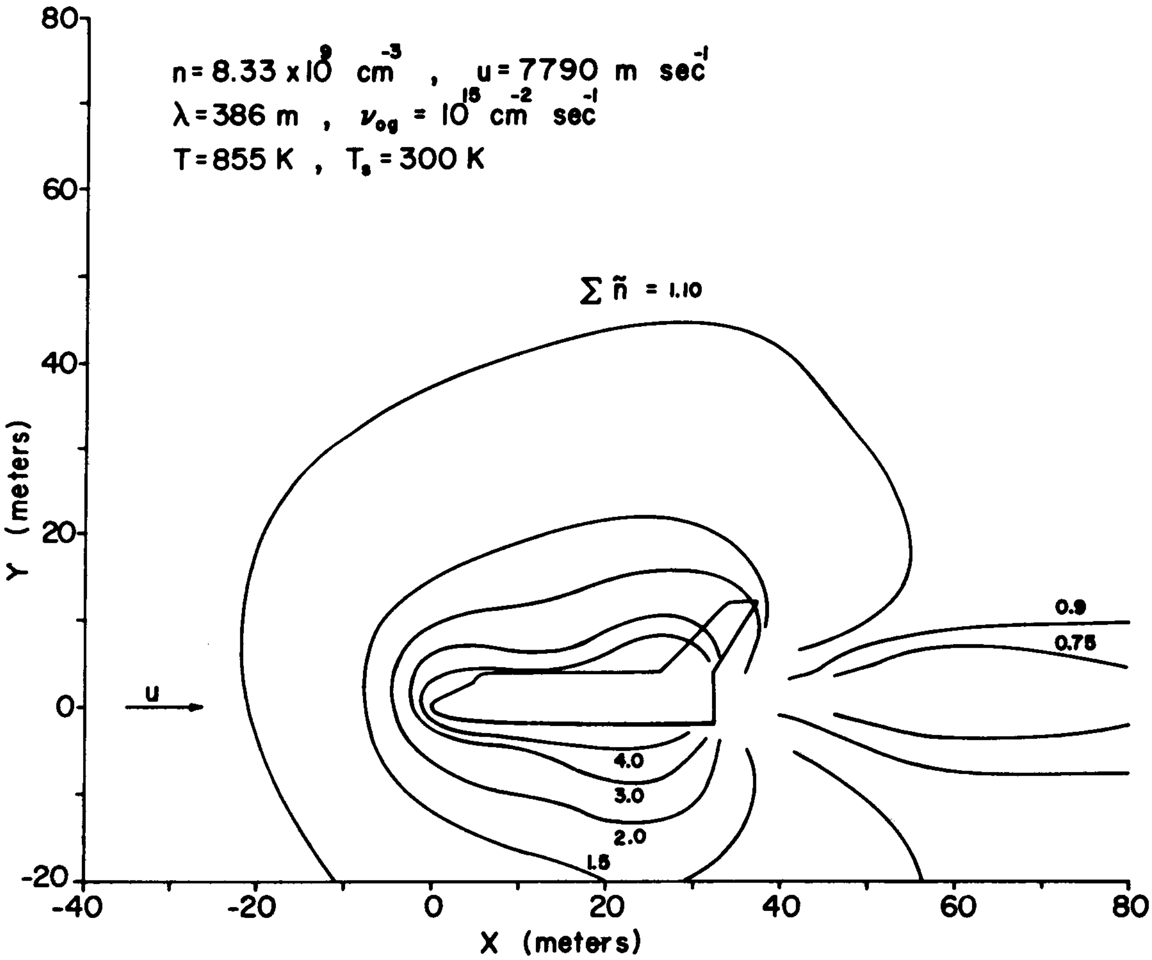

Fig. 9. The total density distribution in the Shuttle midplane, normalized by the undisturbed freestream density $n=8.33 \times 10^{9}$ cm^{-3}. The freestream velocity $u=7790$ m sec^{-1}, the temperature T=855 K, and the mean free path $\lambda=386$ m. The Shuttle surface temperature $T_S=300$ K and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

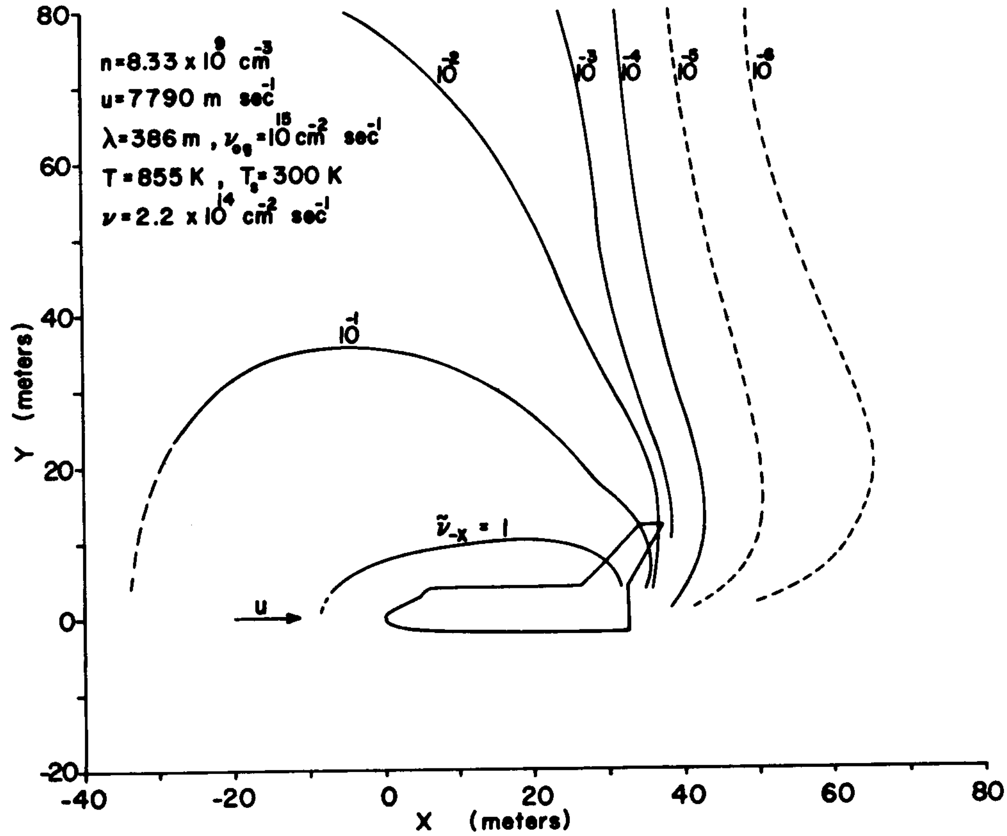

Fig. 10. The upstream flowing flux density distribution (summed over all molecular types) in the Shuttle midplane, normalized by the flux density in the stationary freestream $nv_m/2\sqrt{\pi})=\nu=2.2 \times 10^{14}$ cm^{-2} sec^{-1}. The freestream density $n=8.33 \times 10^9$ cm^{-3}, the velocity $u=7790$ m sec^{-1}, the temperature T=855 K, and the mean free path $\lambda=386$ m. The Shuttle surface temperature $T_s=300$ K and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

Figure 11a gives the molecular flux density incident on typical surface elements near the Shuttle midplane for each molecular type. For surface elements near the aft end of the payload bay, the normalized incident flux density of type 4 molecules (outgassing) exceeds 1. This also implies that sensitive experiments may encounter a severe contamination problem. Figure 11b gives the incident molecular flux relative fraction for each molecular type, averaged over the entire Shuttle surface. The type 4 molecules account for more than 20 percent of the total, although over much of the forward fuselage the type 1 incident flux density exceeds the type 4 by about two orders of magnitude.

Figure 12 gives the column density (molecules/cm^2) in the Shuttle midplane for each molecular type, as viewed from just above the payload bay ($x = 24$, $y = 4$). The angle increment indicated on the figure is 20°. The path length extends to the flow field boundary. The maximum value of the type 4 column density is $5 \times 10^{13} cm^{-2}$.

ACKNOWLEDGEMENT

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REFERENCES

1. Melfi, L. T., Characteristics and potential applications of orbiting ultrahigh vacuum facilities, Acta Astronautica 4:801-811 (1977).

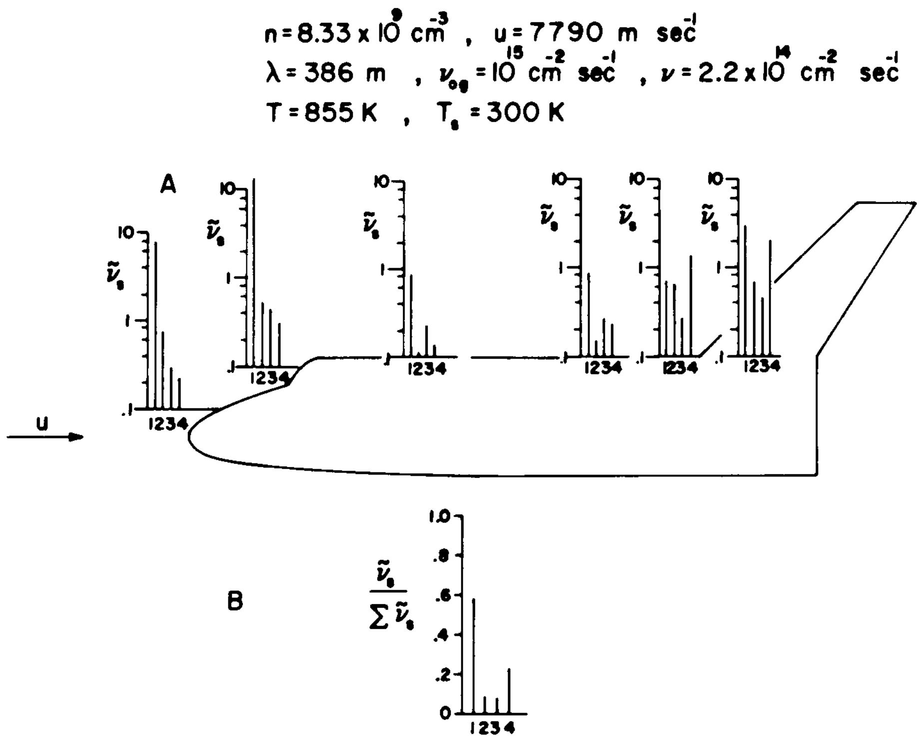

Fig. 11. (a) The molecular flux density incident on several surface elements of the Shuttle near the midplane, normalized by the flux density in the stationary freestream $nv_m/(2\sqrt{\pi})=\nu=2.2 \times 10^{14}$ cm^{-2} sec^{-1}. The incident flux density is given for each molecular type at each location (exponential ordinate). (b) The relative incident flux density for each molecular type averaged over the entire surface of the Shuttle. The freestream density $n=8.33 \times 10^9$ cm^{-3}, the velocity $u=7790$ m sec^{-1}, the temperature T=855 K, and the mean free path $\lambda=386$ m. The Shuttle surface temperature $T_s=300$ K and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

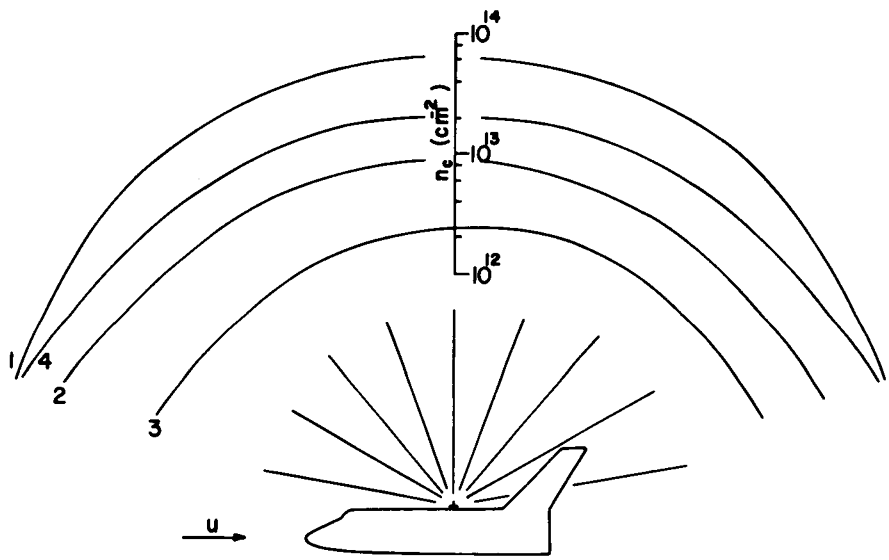

Fig. 12. The midplane column density for each molecular type as viewed from the top of the payload bay (x=24 m, y=4 m), given in molecules per cm^2. The freestream density n=8.33 x 10^9 cm^{-3}, the velocity u=7790 m sec^{-1}, the temperature T=855 K, and the mean free path λ=386 m. The Shuttle surface temperature T_S=300 K and the surface outgassing rate $\nu_{og}=10^{15}$ cm^{-2} sec^{-1}.

2. Bird, G. A., Molecular Gas Dynamics, Oxford University Press (London) 1976.

3. Bird, G. A., Flow field simulation for the space Shuttle orbital vehicle, Proc. 10th Int. Symp. Rarefied Gas Dynamics (1976).